

# PROBING THE SPACE-TIME EVOLUTION OF HEAVY ION COLLISIONS WITH BREMSSTRAHLUNG

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We examine the bremsstrahlung photons emitted in the central collisions of two gold nuclei at the Relativistic Heavy Ion Collider. While the measurements of the final hadrons can reveal only the amount of stopping, they tell us very little about the space-time evolution of the bulk matter in the collisions. By using two extreme collision scenarios, we argue that the low and medium energy bremsstrahlung photons can, not only reveal the amount of stopping, but also the finer details of the space-time evolution of the charges.

## 1 Introduction

Very soon at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory, experiments which could previously only be conducted at energies up to 9 GeV/nucleon can now be done at 100 GeV/nucleon in the centre of mass frame. At these newly attainable energies, the probability for discovering new physics in the form of the formation of an entirely new many-body system under extreme conditions, the so-called quark-gluon plasma (QGP), should be greatly enhanced. There are many important issues that one should address. In this talk, we will focus on baryon stopping and the space-time evolution of the bulk charges in the system.

The information on the degree of baryon stopping is important for several reasons. The presence of net baryon density in the most energetic collision zone will affect the rates of particle production, that of parton chemical equilibration<sup>1</sup>, etc. Theoretical estimates of the signatures of QGP, especially those that assume specific environmental conditions as the starting point, have the need for a reasonably good input of the net baryon concentration. The present method is to measure the rapidity distributions of the hadrons. To do this, detectors must cover at least  $2\pi$  of the collision centre. That means no small number of hadronic detectors will have to be deployed in a hemisphere. The rewards of such experimental efforts are somewhat limited because these measurements will only give us information about the surface of last interac-

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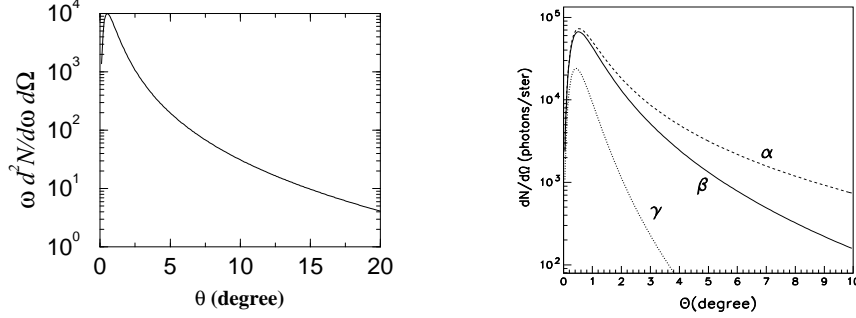


Figure 1. Plot of the intensity of soft photons vs.  $\theta$  for a flat final charge rapidity distribution (left). Plot of the number of soft photons vs.  $\theta$  when there is ( $\alpha$ ) full stopping, ( $\beta$ ) half transparency and ( $\gamma$ ) near complete transparency (right).

tions of the hadrons. They will not tell us how the hadrons actually get there. We will show that an easier method exists for measuring stopping and that it can also provide information on the space-time history of the net charge in the collisions.

## 2 Measuring Charge Stopping with Bremsstrahlung

As the nuclear matter collides in A-A collisions, QCD as the dominant interactions will slow down the relativistically moving nuclei. While this is happening, the simple fact that accelerating charges must emit photons, the intensity of which depends on the accelerations hence the degree of stopping, give us the possibility of measuring stopping by detecting photons instead. The first advantage is only photons need to be detected. We shall see the second advantage shortly that the measurement is highly localized in spatial direction. These should simplify the detector design and construction.

Using the standard formula<sup>2</sup> for the radiation of a time varying current, the initial highly Lorentz contracted nuclei traveling at  $v_0 = \tanh y_0 \sim 1$  represented by the current  $J_i(z, t) = v_0 \sigma \{ \delta(z - v_0 t) - \delta(z + v_0 t) \} \hat{z}$ , becomes  $J_f(z, t) = \sigma \int dy \rho(y) v(y) \delta(z - v(y)t) \hat{z}$  when the charges have a final rapidity distribution  $\rho(y)$ . The intensity can be worked out to be

$$\omega \frac{d^2 N}{d\omega d\Omega} = \frac{\alpha Z^2}{4\pi^2} \sin^2 \theta |F(\omega \sin \theta)|^2 \left| \left[ \int dy \frac{v(y) \rho(y)}{1 - v(y) \cos \theta} - \frac{2v_0^2 \cos \theta}{1 - v_0^2 \cos^2 \theta} \right] \right|^2 \quad (1)$$

at an angle  $\theta$  from the beam or  $z$ -axis. For a flat rapidity distribution, this

is plotted in Fig. 1(left). The maximum intensity is at small angle close to the beam pipe. This is so because Eq. (1) is dominated at small angle by the second term when that denominator is small. This emission in the extreme forward direction is of course a familiar relativistic effect. It is this effect that ensures only a few photon detectors need to be placed at precise locations for these measurements.

Now to see if it is possible to use bremsstrahlung to distinguish between the various degrees of stopping, all we need to do is to draw some  $\rho(y)$  representing different cases and use these in Eq. (1) above. To be able to compare them, they must all give the same total multiplicity. This has been done in ref.<sup>3</sup> and Fig. 1(right) shows that this is indeed possible. Although the region of maximum intensity tends to be close to the beam pipe, this plot shows that it is sufficient to point the photon detectors at a few degrees off the beam axis. So it is clear that by strategically placing a few detectors around the beam pipe, charge stopping can be measured by this much more localized detection method, whereas if hadrons are used for this purpose, many more detectors are required and they must cover a much wider area.

### 3 LEXUS

The above was an illustration of an easier alternative to assessing stopping via hadron rapidity distributions. We now turn to the space-time evolution of the bulk charges in the collisions. To do this, we need a more realistic 2-D rapidity-transverse spatial distribution. This can be readily generated from the LEXUS model<sup>4</sup> which was designed by choice to interpret A-A collisions as two clusters of nucleons undergoing rows on rows of multiple nucleon-nucleon scatterings. In this model, the parton language is deliberately not used at all. The philosophy behind this is that if the generated results cannot reproduce experimental data, then there must be more to the collisions than nucleons colliding with each other. One could interpret QGP formation as an example of one such possibility. Since p-p collisions have essentially hyperbolic cosine distributions, as far as generating nucleon rapidity distribution is concerned, there is only one parameter which is the probability for a nucleon-nucleon collision to be hard as opposed to diffractive or elastic. Once this is fixed from p-p data, the rows on rows of nucleon collisions in Au+Au collisions at RHIC energies can be performed to give the distribution plotted in Fig. 1 of ref.<sup>3</sup>. The shape of this distribution can be captured in a parameterization

$$\frac{d^3Q}{d^2r_\perp dy} = n_0 \frac{Ze}{A} \frac{dl(r_\perp, y)}{dy} = n_0 \frac{Ze}{A} [f(r_\perp) + g(r_\perp) \cosh y] . \quad (2)$$

The functions  $f(r_\perp)$  and  $g(r_\perp)$  can be found in ref.<sup>5</sup>. Using this, the combined radiation amplitude from the target and projectile can be written in terms of the acceleration  $a(y, t)$  as

$$\begin{aligned}
A(\omega, \theta) = & \sin \theta \frac{Ze}{A} n_0 \int_0^R dr_\perp r_\perp J_0(r_\perp \omega \sin \theta) \int_0^{y_0} dy \frac{dl(y, r_\perp)}{dy} \\
& \times \int_{-\infty}^{\infty} dt \exp\{i\omega(t - z(y, t) \cos \theta)\} \frac{a(y, t)}{(1 - v(y, t) \cos \theta)^2} \\
& + \{(z, v, a) \longleftrightarrow (-z, -v, -a)\}. \tag{3}
\end{aligned}$$

This paves the path for what are to follow in the next section.

#### 4 Two Scenarios of Space-Time Evolution

As we mentioned in Sec. 1, measuring hadrons alone will not tell us much about what happened to the bulk of the matter in the intervening period after first nuclear contact but before the final break up of the system. Below, we will show two collision scenarios which follow different space-time paths but both end up with the same final nucleon rapidity-transverse spatial distribution generated from LEXUS. This aspect guarantees that no measurement of the rapidity distribution of final state hadrons will be able to distinguish between them.

The first scenario is Bjorken-like where the nucleons progressively decelerate to the final rapidities. The duration of this deceleration  $t_f$  may or may not depend on how much nuclear matter each nucleon has to transverse. The second scenario is Landau-like in which all nucleons in the two initial nuclear clusters must come to a complete stop instantaneously on initial nuclear contact. Subsequently, the immense pressure existing in the highly excited and compressed region accelerates and drives the nucleons to their final rapidities. The time  $t_f$  required for the bulk matter to finally settle down must be independent of where the individual nucleons or charges are located in the system. The accelerations in both cases are expressed in the simple form

$$a(l, r_\perp) = \{v_f(y) - v_0\} t_f^{-1}(r_\perp) = \{\tanh y - \tanh y_0\} t_f^{-1}(r_\perp). \tag{4}$$

Inserting this into Eq. (3), the bremsstrahlung radiation can be worked out for each scenario.

In Fig. 2, we show just one example of each scenario of comparable time scale. In this specific example, the duration for the deceleration in the Bjorken-like scenario depends on the amount of matter in the path of each nucleon, therefore there is a central oval-shaped charge free region. The

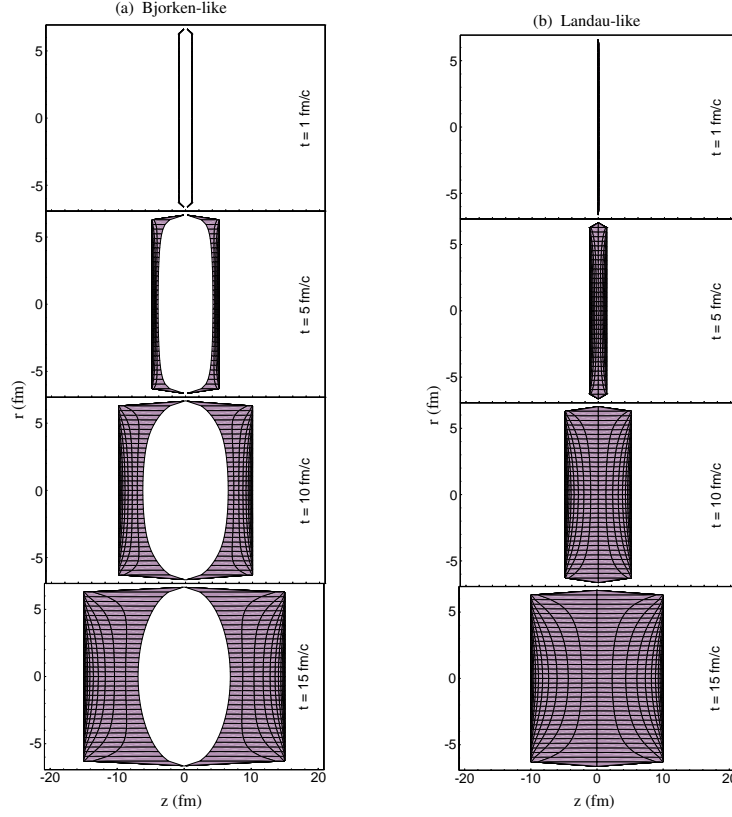


Figure 2. Two scenarios of the space-time evolution in a Au+Au collision.

Landau-like scenario on the other hand has spatially uniform acceleration and therefore there is no electrically neutral zone. In both cases, the highest densities and greatest variations in the concentration of the charges are at the front of the expanding matter as shown by the contours. The temporal-spatial distribution of the charges in the two scenarios are indeed very different even though the final rapidity distributions are the same.

In Fig. 3, the variations of the intensities of the bremsstrahlung emission with the photon energy  $\omega$  in each scenario are plotted at  $\theta = 5^\circ$  for various values of  $t_f$ . Whereas in the Bjorken-like scenario, the intensity is very slowly varying with  $\omega$  and the variation of  $t_f$  makes little difference, the Landau-

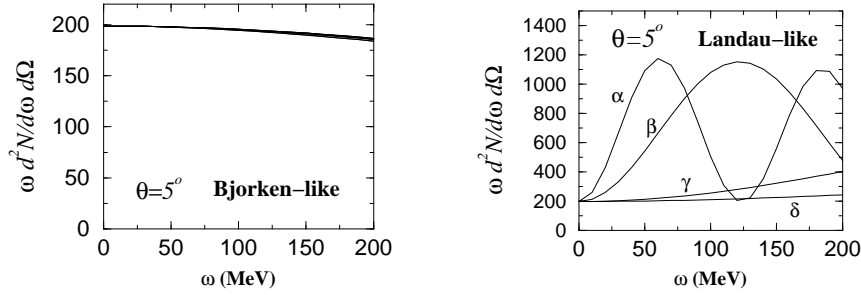


Figure 3. Whereas the bremsstrahlung spectra in the Bjorken-like scenario show almost no dependence on  $t_f$  and very slowly variations with  $\omega$ , the Landau-like scenario shows oscillations and enhancements for  $t_f = 20$  ( $\alpha$ ), 10 ( $\beta$ ), 2 ( $\gamma$ ) and 1 ( $\delta$ ) fm/c.

like scenario shows oscillations with  $\omega$  and the frequency clearly depends on  $t_f$ . Thus by examining the soft photon spectra, it is possible to tell one scenario from the other. In the second scenario, we have an added bonus of being able to measure the time scale for the bulk matter to settle down. The oscillations are a result of interference due to the existence of two components in the acceleration, the instantaneous stopping and the intense pressure driven expansion, of the bulk charges. The interference of the two greatly enhances the intensities and manifests itself as oscillations in the radiation spectrum.

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